Review on Methodologies in Self Healing Concrete

Akshat Shukla[1], Nitesh Gohil[2], Vinay Bhatkar[3]

[1]*Student, Department of Mechanical Engineering Thakur College of Engineering and Technology Mumbai, India*
[2]*Student, Department of Mechanical Engineering Thakur College of Engineering and Technology Mumbai, India*
[3]*Asst. Professor, Department of Mechanical Engineering Thakur College of Engineering and Technology Mumbai, India*

***Abstract*—Concrete is a highly reliable construction material when it comes to building structures. Given its ability to resist high compressive forces, it has its set of deficiencies too. Crack formation is one such failure of the material that science has still not been able to solve. This phenomenon of microcrack formation significantly affects the lifecycle, reliability of the concrete. It becomes crucial to formulate new ways to increase the life of a concrete structure. Result of which was the creation of self-sensing concrete. This paper extensively reviews various approaches to understand self-healing concrete. In addition to that, it explores the shortcomings of the bacterial approach and suggests a fungal approach as it is far more progressive, reliable, and potent of taking the research of Self-Sensing Concrete ahead.**

***Index Terms*—Self Healing Concrete, Concrete, Self Sensing, Smart Concrete, Autogenous Healing, Concrete Reinforcement, Structure Longevity, Bacterial Regeneration.**

I. INTRODUCTION

A. *Crack Formation Theory*

Concrete is a composite material that consists of a curated mixture of cement, rough aggregates, and fine aggregates. It is one of the most commonly used building components in today's age. Usage and application of concrete explain that it can resist the compressive forces subjected due to the load effectively. Even though it is one of the most major construction materials, it cannot handle tension well

[1]. Upon inducing a certain amount of tension on concrete structures, they begin to form micro-cracks. This micro crack formation directly affects the durability of the concrete and often results in a reduction of the strength of the structure. Upon researching further, it was found that along with other factors like pH level of the atmosphere and the amount of load subjected on concrete negatively affects it, the permeability of the concrete was one of the leading causes of the concrete structure failure. Due to an increase in the permeability of the concrete the water easily pass through the concrete and come in the contact with the reinforcement of the concrete structure and after some time corrosion starts, due to this strength of the concrete structure will decrease [2] and cracks will be introduced. Due to accession in the permeability of the concrete, the water smoothly advances through the concrete and get in contact with the reinforcement of the concrete structure and subsequently, corrosion begins due to the aforementioned strength of the concrete structure will drop so it will be required to restore the cracks [3].

B. *Self Healing Concrete*

Smart Material Technology stands as the recently emerging field of research which has a very wide scope in the domain of civil infrastructure and development, in terms of the future. These certain approaches always tend to improve the overall life, longevity, durability, decreasing the failure rate, and considerably enhancing reinforcements. The result of which is a newly enhanced concept with a concrete application [4].

Smart concrete represents the development direction of concrete from high strength and high performance to multi-functionality and intelligence. Self-sensing concrete is a kind of smart concrete that has attracted wide attention from academia and industry [4]. Self-healing concrete therefore can be defined as the concrete possessing a remarkable ability to repair the cracks the structure has developed. Due to very low tensile strength, we often get to see the crack formation in the concrete. These cracks also damage the durability factor of the concrete structure since it paves a way for reacting substances to get introduced. If micro-cracks grow to the reinforcement, the reinforced material experiences corrosion. It becomes vital to heal the crack. The sustainability and the durability and life cycle of the concrete will increase due to self healing technique. [5] [6] Based on the repair capacity of the concrete, it is mainly because moisture and air enter the structure, and a part of the cement particles undergoes hydration reaction. The precipitates accumulate and block the cracks. This method has a significantly low recovery rate [7]. The Precipitation of calcium carbonate has been found out to be the most significant factor controlling the self healing of concrete. [8] [9] Each classical healing model consisted of autogenously healing capabilities of the concrete but with enough research, many chemical approaches were developed; wherein certain chemicals and the leading reactions become the self-healing agents. With more research, the more recent studies follow up an approach of using the products and majorly the bacteria itself as the self-healing agent. In several published studies the potential of calcite precipitating bacteria for concrete or limestone surface remediation or durability improvement was investigated. [10] The mechanism of bacterially mediated calcite precipitation in later studies was primarily based on the enzymatic hydrolysis of urea. One noteworthy drawback of this method is that in turn, it introduces the environmental nitrogen in excess. [11] Hence, what can be understood of the self-healing concept in today's date is that it is healing or recovery of at the very least one property of the concrete that may decrease the chances of failure in that structure. However, majorly we will study the crack formation and later, the healing of the micro-cracks using multiple approaches. Therefore, with the mention of cracks alone, it is understood that the factor in which healing will take place will be the permeability property of the structure [10]. The permeability of the structure with smaller crack will be less than that of a larger crack [12] [13].

II. METHODOLOGIES TO INGRAIN SELF-HEALING ABILITY IN CONCRETE

A. Autogenous Self-healing

Autogenous healing is the type of healing that is promoted inherently by the concrete itself without the help of any external factors such as additives. Autogenous healing is promoted by the presence of dry cementite material which can still rehydrate to react and fill the crack or by the formation of Calcium Carbonate ($CaCO_3$) or Calcium Hydroxide ($Ca(OH)_2$). Cracks can also be filled due to the swelling of the cementite surface. Autogenous Healing requires the presence of moisture and the absence of tensile strength to facilitate the filling of micro-tears in the concrete. This method works for tears ranging from 50μm to 150μm with full recovery being possible under 50μm after wet-dry cycles. [14] Autogenous and natural self-healing happens because of the crystallization of calcium carbonate. In the reaction, CO_2 emerges from the air and the calcium ion Ca^{2+} is derived from concrete. The reactions involved are: [15]

$$H_2O + CO_2 \leftrightharpoons H_2CO_3 \leftrightharpoons H^+ + HCO_3^- \leftrightharpoons 2H^+ + CO_3^{2-}$$

$$Ca^{2+} + CO_3^{2-} \leftrightharpoons CaCO_3 \quad (\text{pH of water} > 8)$$

$$Ca^{2+} + HCO_3^- \leftrightharpoons CaCO_3 + H^+ \quad (7.5 < \text{pH of water} < 8)$$

B. *Microcapsules containing polymers or minerals*

Ideas to develop self-healing concrete using microcapsules have been in rounds after White et al. proposed the idea of healing polymer composites using microcapsules [16].

Microcapsules are micron-sized particles having a shell that encapsulates a glue or a solvent. Different microcapsules acting as a resin and hardener as a two-part epoxy system can also be used. Such capsules can be mixed with the aggregate and the cement mix to form a mixture that contains a percentage of liquid resin that can flow in the cracks developed in the concrete after undergoing cyclic stresses. As suggested by H.M. Andersson et al. in Self Healing Polymers and compos-ites, Poly Urea-Formaldehyde, Polyurethane Microcapsules, and Grubbs' catalyst inside wax protected microspheres as discussed by White et al. can be used. Self-healing using microcapsules seems a viable method to prolong concrete life. Microencapsulated walls show greater healing capability than conventional walls as studied by Al-Tabbaa et al. in the UK fields study. The microcapsules used comprised of sodium silicate as the cargo embedded in an emulsion with mineral oil [17].

C. *Healing with Resin filled hollow fibers*

Biological organisms employ a vascular structure that can transport necessary fluids to maintain the temperature, assist in aerobic activity, and supplant necessary healing to keep the tis-sues alive. A similar networking technique can also be applied in the concrete structure, so that once the crack formation takes place, the binder material can supply resin, thereby recovering the lost strength of the concrete. [18]. Resin-filled hollow fibers provide an advantage against microcapsules since they can provide structural reinforcement to the specimen. Instead of being spread randomly like the microcapsules, they can be integrated as required at places that are more prone to failure. Also, unlike microcapsules, hollow fibers do not leave empty spaces which increases the stress concentration. However, they prove to be costly and time-consuming to embed into the product as compared to the microcapsules. Hollow Glass Fibres can be embedded into the concrete to provide healing ability as discussed in [19]. A Hollow Glass Fibre between 30-100μm with hollowness around 50% was embedded with glass fiber reinforced plastic to emulate self-healing. The repair agent flows into the damaged zone when cracks are formed due to loading.

D. *Biological Approach in Self-healing concrete*

Biological Approach makes use of bacteria that are Alkali resistant and can form spores to fill the cavity that is created after damage. Bacteria apt for the purpose include *B. cohnii*, *B. pseudofirmus*, and *B. sphaericus*. H.M. Jonkers et al. [11]

[15] studied the viability of bacteria incorporated concrete. Portland cement was mixed with tap water and *B. cohnii* bacteria spores. The specimen recovered at room temperature. The specimen contained 1-10 ×108 spores per cm-3 of concrete with dimensions of 4 cm ×4 cm ×4cm. The survival rate was then observed by estimating the number of viable bacteria present by the MPN (most probable number) method. It was found that for two size classes of 0.01-0.1 μm and 0.1-1 μm, an abundance in the quantity from larger pores in specimens cured for 3-7 days was observed as compared to the smaller pores cured for 28 days. The majority of added organic compounds resulted in significantly reduced strength development except for the addition of calcium lactate which did not substantially affect the compressive strength.

Along with the known bacterium above mentioned, B. cohnii, *B. pseudofirmus*, and *B. sphaericus*, some other type of bacteria are also used to fulfill other roles which are always required while considering self-healing. Certain bacterium like *B. pasteurii, Deleya Halophila, Halomonasrurihalina, Myxococcus Xanthus*, and *B. megaterium* are majorly used for crack healing processes. B. sphaericus is used as an agent for surface treatment [20]. Often, when a lot of time is passed which surpasses the functioning time of the selected bacteria, the bacterial spores lay dormant. When cracks occur, and water finds its way in, the dormant bacterial spores will be activated and form calcium carbonate to heal the crack.. As the crack heals, the bacteria within, will be deactivated. With time, the environmental conditions turn in the favor of the spore; these spores can be activated again. For the cracks which pre-exist, spore or bacterial culture can be introduced [21]. The study on self-healing concrete is limited to bacteria only [11] [21] [22-35].

E. *Fungal Approach in Self-healing Concrete (Scope)*

For as long as the overall progress of self-healing concrete is concerned, the research has extensively been focusing on the bacteria meditated approach alone. But it is to be noted that, there is a far better approach available which in itself becomes the scope of this research. To begin considering fungi as the potential candidate for self-healing research, the following are a few reasons:

- There has been little success concerning long-term self-healing efficacy.
- There has been little success concerning the repair of wide cracks or rapid crack repair.
- Incorporation of healing agents i.e., Bacterial spores result in the loss of concrete compressive strength [36].

Decade-long researches have been supporting the bacterium approach to an extent that there is next to no information available on the genomes of fungi that represent or possess such a self-healing capability. There are a few logically researched intuitive concepts that just might be able to support a scientific view that the paradigm shift supports fungi as the next candidate for self-healing research. The first and foremost point naturally becomes that 'Fungi mediated self-healing concrete may possess long term self-healing capacity [36]. Certain species of fungi have evolved the ability to adapt to a range of so-called extreme environments, where few other microorganisms could survive [37]. According to Magan (2007), many different species of fungi can grow in alkaline environment. For example, *Paecillomyces lilacimus and Chrysosporium spp*. are both alkaliphilic and able to grow very well at pH-values below 11. Genetically engineered fungi are also considered as important candidates for self-healing concrete [38].

Fungi-mediated self-healing concrete may heal wider cracks within shorter periods [36]. Fungi generally grow either in the yeast-like form or possessing filamentous structure. The cells of filamentous fungi grow *hyphae*, creating a branched net called *mycelium*. It is widely believed that filamentous fungi possess distinctive advantages over other microbial groups to be used in a variety of applications of bio-mineralization-based technologies due to their superior cell wall-binding capacity and extraordinary metal-uptake capability [36] Incorporation of Healing Agents, i.e., Fungal Spores and Nutrients, Could Lead to No Negative Consequences on Concrete Compressive Strength [36].

III. CONCLUSION

With the extensive study carried on Self Healing Concrete for the past decade, it has been observed that the majority of research was done only on bacterial approach and the fungal approach was left unexplored. The bacterial approach, which may be superior to the Natural and Chemical approach, has a considerable amount of limitations that no longer can be overlooked. The overall speed of progress is hindered solely due to limiting the perspective to the bacterial approach. The scope must be extended to the fungal approach, given its extraordinary mineralization technique.

REFERENCES

[1] Milan, Sneha, 2018,'Experimental Study on Strength Characteristics of Self–Healing Concrete with Fly Ash', IRJET, vol 06, issue 06, pp. 1

[2] Use of bacteria to repair cracks in concrete by Kim Van Tittelboom a, Nele De Belie a,*, Willem De Muyncka, b, Willy Verstraete b., 2008.

[3] Willem et al., 2008

[4] Self-Sensing Concrete in Smart Structures. http://dx.doi.org/10.1016/B978-0-12-800517-0.00011-3

[5] Abrams D. Autogenous healing of concrete. Concrete 1925;27(2):50. Dry C. Matrix cracking repair and filling using active and passive modes for smart timed release of chemicals from fibers into cement matrices. Smart Mater Struct 1994;3(2):118–23

[6] Tittelboom KV, Belie ND. Self-healing in cementitious materials-a review. Materials 2013;6:2182–217

[7] Wei Wang, 2019, 'Research Status of Self Healing Concrete', IOP Conf. Series: Earth and Environmental Science 218 (2019) 012037

[8] Edvardsen C. Water permeability and autogenous healing of cracks in concrete. ACI Mater J 1999;96:448–54

[9] Hearn N. Self-sealing, autogenous healing, and continued hydration: what is the difference? Mater Struct 1998; 31:563–7

[10] Virginie Wiktor, 2011, 'Quantification of crack-healing in novel bacteria-based self-healing concrete', Cement and Concrete Composites

[11] Jonkers HM, Thijssen A, Muyzer G, Copuroglu O, Schlangen E. Application of bacteria as self-healing agent for the development of sustainable concrete. Ecol Eng 2010;36:230–5

[12] Rapoport J, Aldea CM, Shah SP, Ankenman B, Karr AF. Perme-ability of cracked steel fiber-reinforced concrete. J Mater Civil Eng 2002;14(4):355–8P

[13] Hoseini M, Bindiganavile V, Banthia N. The effect of mechanical stress on the permeability of concrete: a review. Cem Concr Compos 2009;31:213–20)

[14] Zwaag, Sybrand. Self Healing Materials, Delft, Springer, 2007

[15] Qureshi, Tanvir, and Abir Al-Tabbaa. Self-Healing Concrete And Cementitious Materials. 2021, https://www.intechopen.com/books/advanced-functional-materials/self-healing-concrete-and-cementitious-materials.

[16] White, S. R., Sottos, N. R., Geubelle, P. H., Moore, J. S., Kessler, M. R., Sriram, S. R., . . . Viswanathan, S. (2001). Autonomic healing of polymer composites. Nature, 409(6822), 794–797. doi:10.1038/35057232

[17] Al-Tabbaa, A., Litina, C., Giannaros, P., Kanellopoulos, A., & Souza, L. (2019). First UK field application and performance of microcapsule-based self-healing concrete. Construction and Building Materials, 208, 669–685. doi:10.1016/j.conbuildmat.2019.02.178

[18] Trask, R. S., Williams, H. R., & Bond, I. P. (2007). Self-healing polymer composites: mimicking nature to enhance performance. Bioinspiration& Biomimetics, 2(1), P1–P9. doi:10.1088/1748-3182/2/1/p01

[19] Self Healing Fibre-reinforced Polymer Composites: An Overview

[20] Salmabanu, Suthar, 2015, 'A Review on Self Healing Concrete', Journal of Civil Engineering Research 2015, pp. 53-58)

[21] EPOfilms, 2018. Jin, Congrui et al. "Fungi: A Neglected Candidate For The Application Of Self-Healing Concrete". Frontiers In Built Environ-ment, vol 4, 2018. Frontiers Media SA, doi:10.3389/fbuil.2018.00062. Accessed 11 July 2021

[22] Fortin, D., Ferris, F. G., and Beveridge, T. J. (1997). Surface-mediated mineral development by bacteria. Rev. Mineral. 35, 161–180.

[23] Stocks-Fischer, S., Galinat, J. K., and Bang, S. S. (1999). Microbiolog-ical precipitation of CaCO3. Soil Biol. Biochem. 31, 1563–1571.

[24] Bang, S. S., Galinat, J. K., and Ramakrishnan, V. (2001). Calcite precip-itation induced by polyurethane-immobilized Bacillus pasteurii. Enzyme Microb. Technol. 28, 404–409. doi: 10.1016/S0141-0229(00)00348-3

Bang, S. S., Lippert, J. J., Yerra, U., Mulukutla, S., and Ramakr-ishnan, V. (2010). Microbial calcite, a bio-based smart nanomaterial in concrete remediation. Int. J. Smart Nano Mater. 1, 28–39. doi: 10.1080/19475411003593451

[25] Ramachandran, S. K., Ramakrishnan, V., and Bang, S. S. (2001). Remediation of concrete using micro-organisms. ACI Mater. J. 98, 3–9. doi: 10.14359/10154

[26] Dick, J., De Windt, W., De Graef, B., Saveyn, H., Van der Meeren, P., De Belie, N., et al. (2006). Bio-deposition of a calcium carbonate layer on degraded limestone by Bacillus species. Biodegradation 17, 357–367. doi: 10.1007/s10532-005-9006-x

[27] Ramakrishnan, V. (2007). "Performance characteristics of bacterial concrete: a smart biomaterial," in Proceedings of the 1st International Conference on Recent Advances in Concrete Technology (Washington, DC), 67–78.

[28] De Muynck, W., De Belie, N., and Verstraete, W. (2010). Microbial car-bonate precipitation improves the durability of cementitious materials: a review. Ecol. Eng. 36, 118–36. doi: 10.1016/j.ecoleng.2009.02.006

[29] Jonkers, H. M., and Schlangen, E. (2009). A two component bacteria-based selfhealing concrete," in Concrete Repair, Rehabilitation and Retrofitting II, eds M. G. Alexander, H. D. Beushausen, F. Dehn, and P. Moyo (Boca Raton, FL: CRC Press, Taylor and Francis Group), 119–120.

[30] Van Tittelboom, K., De Belie, N., Van Loo, D., and Jacobs, P. (2011). Self-healing efficiency of cementitious materials containing tubular capsules filled with healing agent. Cem. Concr. Comp. 33, 497–505. doi: 10.1016/j.cemconcomp.2011.01.004 [31] Jonkers, 2011

[31] Wang, J., Van Tittelboom, K., De Belie, N., and Verstraete, W.(2012). Use of silica gel or polyurethane immobilized bacteria for self-healing concrete. Constr. Build. Mater, 26, 532–540. doi:10.1016/j.conbuildmat.2011. 06.054

[32] Wang, J. Y., Snoeck, D., Van Vlierberghe, S., Verstraete, W., and De Be-lie, N. (2014b). Application of hydrogel encapsulated carbonate precip-itating bacteria for approaching a realistic self-healing in concrete. Con-str. Build. Mater. 68, 110–119. doi: 10.1016/j.conbuildmat.2014.06.018 Wang, J. Y., Soens, H., Verstraete, W., and De Belie, N. (2014a). Self-healing concrete by use of microencapsulated bacterial spores. Cem. Concr. Res. 56, 139–152. doi: 10.1016/j.cemconres.2013.11.009

[33] Ersan, Y. C., De Belie, N., and Boon, N. (2015a). Microbially induced CaCO3 precipitation through denitrification: an optimization study in minimal nutrient environment. Biochem. Eng. J. 101, 108–118. doi: 10.1016/j.bej.2015.05.006

[34] Khaliq, W., and Ehsan, M. B. (2016). Crack healing in concrete using various bio influenced self-healing techniques. Constr. Build. Mater. 102, 349–357. doi: 10.1016/j.conbuildmat.2015.11.006 [36] Seifan et al., 2016

[35] Zhang, J., Liu, Y., Feng, T., Zhou M. Zhou, A., et al. (2017). Immobilizing bacteria in expanded perlite for the crack self-healing in concrete. Constr. Build. Mater. 148, 610-617 doi: 10.1016/j.conbuildmat.2017. 05.021

[36] Jin, Congrui et al. "Fungi: A Neglected Candidate For The Application Of Self-Healing Concrete". Frontiers In Built Environment, vol 4, 2018. Frontiers Media SA, doi:10.3389/fbuil.2018.00062. Accessed 11 July 2021

[37] Magan, 2007

[38] Lamb et al., 2001; Caracuel et al., 2003a,b; Nobile et al., 2008; Penalva et al., 2008; Hervas-Aguilar et al., 2010.